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MODERN TOOLS TO EVALUATE AND OPTIMIZE FIRE PROTECTION SYSTEMS

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MODERN TOOLS TO EVALUATE AND OPTIMIZE FIRE PROTECTION SYSTEMS

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N.J. Alvares & H.K. Hasegawa

Abstract

Modern techniques, such as fault tree analysis, can be used to obtain engineering descriptions of specific fire protection systems. The analysis allows establishment of an optimum level of fire protection, and evaluates the level of protection provided by various systems. A prime example: The application to fusion energy experiments.

Introduction

Fusion energy systems may be the ultimate source of stationary electrical power within the next 50 years. Currently, there are several strategies for obtaining the conditions of fusion. Each method primarily involves confining a hydrogen isotope plasma so that the product of plasma density and time can achieve a critical value (The Lawson Criteria where density (η) X time (τ) = 10^{14} ion-sec) where fusion to helium occurs, accompanied by the release of heat and fast neutrons. This process is roughly analogous to the chemical reactions of combustion, correspondingly; initiating the fusion reaction is called "ignition."

Two generic confinement philosophies for obtaining the density-time product leading to fusion ignition are available:

- Inertial confinement, where high energy beams are focused on a minute target of fuel gas creating an extremely high density for very short periods (Figure 1).
- Magentic confinement, where ionized fuel is contained (or for some systems compressed) by magnetic fields at relatively low density. In these systems the period of confinement is substantially longer (Figure 2).

Regardless of the strategy used, each is extremely complex and require

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special accommodations and provisions. Typical facilities necessary for fusion experiments include:

- Large electrical power systems and switch yards.
- Cryogenic plants for superconducting magnets.
- Complex vacuum systems.
- Computer complexes for control, diagnostic and research purposes.
- Laser systems, both for inertial energy supply and for sophisticated diagnostic purposes.
- High-voltage, neutral-beam accelerators for plasma heating.
- Clean rooms for maintaining sensitive electrical and optical equipment.

In direct support of these facilities are:

- Large machine- and mechanical-fabrication shops.
- Electrical and electronic shops.
- Maintenance and clerical support.
- Computer maintenance and repair personnel.
- Specific supply repositories.
- Health and safety services.

Figure 3 illustrates the components of MFTF (Mirror Fusion Test Facility) at the Lawrence Livermore National Laboratory (LLNL) and the complexity of fusion energy experiments.

In an emerging technology like the development of fusion energy, it is likely that systems will evolve that provide a new spectrum of danger to the experimenters and support personnel. In addition, the potential for destructive accidents can be so extensive as to interfere with programmatic progress or cause project cancellation, should the amount of damage exceed some critical proportion of the capital worth of the facility. Moveover, because current fusion experiments are the precursors of tommarrow's fusion-power reactors, it is important to ensure that all hazards are identified and controlled.

Fusion-energy experiments operate with periodic surges of huge quantities of electrical and/or optical energy which generally results in the production of 10^{16} to 10^{19} neutrons per input pulse and equivalent intense thermal stresses. These energy surges create special safety problems that must be addressed in the planning stages of the experiments. The safety problems are multidiciplinary in nature, e.g.,

- Ionizing and nonionizing radiation
- Stray magnetic fields
- Electrical discharge and electric shock
- Stray laser beam effects
- Chemical toxicity
- Fire and smoke effects

Because many of these problems can occur simultaneously, integrated applications of safety techniques are required to affect solutions to potential safety faults.

APPROACH

We believe that a research protocol must be established where safety science is developed at a parallel rate to engineering and scientific advances of emerging energy technologies. To this end, we are involved in a modest program funded by the Operational and Environmental Safety Division (OES) of the Department of Energy (DOE) to ensure that fire protection measures for fusion energy experiments (FEE) evolve concurrently with the advances in fusion energy development. Effective for fire protection for FEE requires adequate knowledge of the normal operation of generic fusion experiments so that faults resulting in unwanted fire can be effectively prevented or protected against.

Our initial efforts were concentrated on learning the operational characteristics of selected FEE's and identifying easily defined fire-risk conditions that exist contemporarally, or that were projected by operating personnel[1]. Our next step was to conduct detailed studies into the interaction between fire hazard and fire protection in Lawrence Livermore National Laboratory (LLNL) FEE's. We used available analytical techniques for assessing fire risk and accepted statistics for determining potential fault modes of operational automatic fire protection systems (FPS)[2].

We intended to follow the analytical protocol diagrammed in Figure 4. Note that our ultimate goal, a risk assessment of the facility, is contingent on an adequate understanding of the three input parameters to the flow chart, i.e., fire growth, FPS reliability, and FPS effectiveness. We were already aware that the state of the art of fire-growth analysis for large enclosures containing complicated fuel arrays was very primitive. We also knew that very little quantitative data are available about the effectiveness of automatic fire-protection systems in a wide variety of fire scenarios. However, we mistakenly believed that sufficient quantitative information existed on the operational characteristics and reliability of FPS's. In fact, we found minimal data regarding system components. Thus, our first task was to understand the functions of existing FPS used in contemporary fusion experiments.

ANALYSIS PROTOCOL FOR FIRE MANAGEMENT SYSTEMS

We used fault-tree analysis[3] as a tool to help us understand the operation of fire-management systems for specific magnetic and inertial confinement fusion experiments at LLNL. Fault trees are diagrams that describe an undesired event by accounting for all elements that comprise the system of interest. The fault tree is structured so that the undesired event appears at the top of the tree. The sequence of events that leads to a system failure is shown below the top event. These events are logically linked to the undesirable event by branches which are in turn linked to standard "or" and "and" gates. The fault-mode operation of these items are assessed by evaluating their position relative to these logic gates in terms of the operational parameters below the item and the results of the operations above the item. Each event is both qualitatively and quantitatively analyzed using codes based on the concepts of Boolean Algebra [4].

Perhaps the most useful qualitative aspect of fault trees is to provide a vehicle for discussion between the analyzer and persons familiar with the analyzed system, i.e., it's possible to construct the tree in a variety of ways, but the results would be questionable if there was no iterative discussion between the systems designer and the fault-tree analyst.

Figure 5 shows the upper layers of a fault tree for the system shown schematically in Figure 6. This system is installed in an enclosure that contains magnetic fusion experiments (MFE). In this case, the top event is the failure of a modified pre-action sprinkler system to emit water, assuming that the intensity of the fire was sufficient to activate a perfectly working system.

The entire tree has about 4 times the components shown in Figure 5. Figure 7 shows a hypothetical subsection of the total tree indicating the relationships and detail possible in the matrix of fault trees.

Using the computer code FTAP[5], we found a total of 713 minimal cutsets (system failure modes) for our unit model. We classified these cutsets according to order, i.e., according to the number of basic events they contained. For example, if a minimal cutset contained a single-point failure, it was of order 1; if it contained two event failures, it was of order 2; etc. Of the 713 minimal, cutsets 42 were of order 1, 32 were of order 2, 14 were of order 3, and 625 were of order 4.

Of the 42 single-point failures, 18 involved component failures in the fire-indicating and zone-indicating units; 5 involved human error, performance-related failures, or secondary failures in the sprinkler heads or the smoke detectors; 1 involved the unavailability of offsite power for more than 24 hours; 1 involved the unavailability of service water; and 17 involved component failures in the piping and valving system.

The minimal cutsets of orders 2 through 4 involved a combination of (1) primary failures in the smoke detectors, (2) primary failures in the sprinkler heads, and (3) failures in the electrical and hydraulic components. Quantitative analysis of the failure probability for the entire fire management ensemble requires iteration of the component reliability and system maintenance.

Components of the fire-protection system were subjected to one of the following three maintenance actions:

- No repair.
- Announced failure.
- Unannounced failure.

An undetected plug in the drypipe system, for example, is a no-repair case.

To calculate the failure of system components, we had to know the following reliability parameters:

- Failure rate, λ (the conditional probability of failure).
- Inspection interval, θ (3 months for the 2XIIB fire protection system).
- Repair time, T.

We used the computer code IMPORTANCE[6] to calculate (1) system unavailability and (2) the quantitative importance of basic events and minimal cutsets contributing to system failure. Our results showed that the probability of a system failing upon demand (i.e., in the event of a fire) is 0.18 and 9 basic events could contribute to its failure. In Table 1 these events are listed and ranked according to their relative importance in contributing to system failure.

A similar analysis was made on a facility entirely committed to a major inertial fusion experiment (IFE). Figure 8, a block diagram of the elements of the IFE fire-management systems, shows the relationship between the detection and response circuits. Wet-pipe sprinkler arrays are the primary fire-suppression components for the high bay experimental areas. These units are inherently more fail-safe than the dry-pipe, pre-action systems that protect the magnetic fusion experiment. Note that the critical components of both the magnetic- and inertial-fusion fire-management systems are the zone- and fire-indicating units (ZIU & FIU).They are extremely imporant because they relay any problem or an emergency signal directly to the fire department's 24-hour dispatch unit. In addition, they provide the power to most of the automatic detection units.

Each system has its own peculiarities of responding to a fire situation. In the MFE pre-action system, (see Figure 6) if certain critical electrical components in the ZIU or FIU fail, no signal would be relayed to the fire department. As a result, the pre-action valve would not receive a fire confirmation signal from the detector circuit and would not open. Consequently, no water would be available to the sprinkler branches.

In the IFE fire-management system, however, this problem is significantly reduced because of the presence of the independent wet-pipe sprinkler systems. These sprinklers will operate regardless of the condition of the FIU/ZIU circuits. However, the fire department's arrival would be delayed until they received a manual response from some other source. Figure 9 schematically compares the relative complexity of both fire-management systems.

Figure 10 highlights the differences in the basic design of the experiments and structures housing the MFE (2XIIB & BETA II) and IFE (SHIVA/NOVA). Perhaps the most notable difference is the age of the structure. The IFE building was designed specifically for that operation. Enclosure boundaries were installed to serve a variety of purposes (e.g. demarking generically different experimental areas, protection from ionizing radiation, fire barriers, and atmospheric control). Both life-support and fire-protection appliances are modern and designed to address the problems of specific experimental components.

The MFE is contained in a building constructed almost two decades ago (Bldg. 435). It was designed for initial experiments on mirror fusion and has housed six major experimental machines and a host of small fusion-related experiments since its construction. Originally, the building did not have any automatic fire-protection capability. But, when the capitol value and complexity of the experiments increased, mandatory fire-protection measures were authorized by the federal agencies that fund the program. Fire-management improvements have been added over the years to establish the present system. The requirement for a dry-pipe, pre-action system coupled to the smoke detector array was specified to ensure that water would not be accidentally released on the experiment. This specification was made because of the concern of the project electrical engineers about electrical shock hazards.

COMPARATIVE RESULTS

Using fault tree analysis, we determined the fault modes and failure rates for the total SHIVA fire management system. Table 2 lists the preliminary results based on this analysis. The most important findings were the high reliability of the wet-pipe sprinkler system and the relatively minor role played by the ZIU/FIU circuits in the reliability analysis. We were unable to complete quantitative analysis for the incipient fire detection circuit* or the Halon 1301 computer fire-suppression systems# because of the lack of available information about their components.

In Table 3 the probability of the wet-pipe sprinkler and the dry pipe preaction sprinkler system failing is compared. Because the operation of the dry-pipe preaction system depends so heavily on the ZIU/FIU circuits, its chance for failure upon demand is nearly 10 times that of the wet-pipe system.

We also analyzed the possibility of an inadvertent release of water from the dry-pipe system as a result of component failure. (Note, human error was not factored into this analysis). Our calculated value of approximately 10^{-6} per year is comparable to industrial experience for wet-pipe systems. Hence, the propensity for electrical engineers to specify waterless fire-protection systems because of a concern over shock hazards is unfounded by accepted engineering analysis. Moreover, the reliability of water intensive fire protection systems is established in the same way.

* The incipient fire detection system senses smoke particulate in the exhaust plenum of ventilation ducts of the laser amplifier section of the SHIVA experiment.

This is an under-floor suppression system designed to suppress fires that might occur in the innumerable electrical power and signal cables necessary for computer operations.

CONCLUSIONS

Our calculations of system reliability are based on incomplete data because component reliability information is sparce, and for some items nonexistent. Our sources for reliability and failure-rate data included:

- Factory Mutual Corporation
- National Fire Protection Association
- United Kingdom Atomic Energy Agency
- IEEE Standard #500
- Wash - 1400 (Reactor Safety Study)

In addition to these sources, and when no documented information was available, we surveyed local and national organizations that had pertinent expertise on the subject for facts, estimates, and conjectures about the performance of fire-management components and systems. To confirm our analyses, we compared our results of the probability of a "successful" sprinkler system operation with statistics of sprinkler system effectiveness accumulated in the commercial sector (Table 4). We are quite encouraged by the agreement between data based on historical experience and our parametric analysis.

Figure 11 reiterates our program objectives. We have established the value of fault tree analysis as an analytical tool for defining the engineering performance and fault modes of contemporary fire protection systems (items B & C). We have used these results to evaluate, on a limited basis, a wide variety of international fusion experiments; and, we are currently developing a protocol for field-safety engineers to use to evaluate the level of fire protection.

Contemporary fire growth analysis is mainly concentrated in the area of residential fire problems. Our attempts to extrapolate promising theories to the industrial scale common to fusion energy experiments, results in a family of temporal fire growth parameters which vary by 100% in both time and intensity. This range is unacceptable, however, we have been able to identify critically needed experimental data, which could reduce the variability of the modeling results.

Figure 12 is a conceptual picture of the impact of unwanted fires on the components used in fusion experiments. Ideally, when our program is completed, we should be able to quantify the coordinates and define the structure of the damage curves. In addition, by defining the performance and effectiveness of the fire management systems we should be able to reduce fire risk to the level where the probability of a significant fire exceeding unacceptable levels will be vanishingly small.

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Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

REFERENCES

[1] N. Alvares, A. Lipska, Assessment of Fire Hazards in Buildings Housing Fusion Energy Experiments, Preprint UCRL 81072. May 2, 1978.

[2] N. Alvares, and H. Hasegawa, "Fire Hazard Analysis For Fusion Energy Experiments", Fire Safety Journal, 2(1979/80), Preprint UCRL 82320. May 2, 1979.

[3] H. Lambert, "Systems Safety Analysis and Fault Tree Analyses", UCID 16238, May 9, 1973.

[4] G. Naanep, H. Lambert and H. Hasegawa, "Fire Protection Study of the 2X11B Mirror Fusion Facility: Fourth International System Safety Conference, Proceedings. July 9, 1979.

[5] R.R. Willie, "Computer Aided Fault Tree Analysis", Operations Research Center, University of California, Berkeley, Rept. ORC 78-14 (1978).

[6] H.E. Lambert and F.M. Gilman, "The Importance Computer Code", Lawrence Livermore Laboratory, UCRL-79269 (1977).

TABLE 1 BASIC EVENTS CONTRIBUTING TO SYSTEM FAILURE

BASIC EVENT	RANK	IMPORTANCE[b]
SMOKE IS INADEQUATE TO IONIZE BOTH DETECTORS	1	.27
HEAT IS INADEQUATE TO FUSE ALL FOUR SPRINKLER HEADS	1	.27
RECTIFIER CR5 FAILS OPEN CIRCUITED[a]	2	.12
RECTIFIER CR1 FAILS OPEN CIRCUITED[a]	2	.12
RECTIFIER CR2 FAILS OPEN CIRCUITED[a]	2	.12
HEAT IS OBSTRUCTED FROM ALL FOUR SPRINKLER HEADS	3	.05
ALL FOUR SPRINKLER HEADS ARE INSTALLED IN THE WRONG POSITION	3	.05
FUSE F3 FAILS OPEN CIRCUITED[a]	4	.03
SWITCH S4-3 FAILS OPEN CIRCUITED[a]	5	.01

[a] FAILURES WITHIN THE ZONE-INDICATING UNIT OR THE FIRE-INDICATING UNIT ARE ALWAYS UNANNOUNCED.

[b] DEFINED AS THE PROBABILITY THAT THE BASIC EVENT OCCURS DIVIDED BY THE PROBABILITY OF THE TOP EVENT.

TABLE 2 PRELIMINARY RESULTS

FPS SIGNAL-RESPONSE ANALYSIS

MAJOR SYSTEM SUBSYSTEMS	AVAILABILITY PER DEMAND	RANGE OF FAILURES (F) OF SUBSYSTEM COMPONENTS FOR A "SUBSYSTEM FAILURE'
HALON 1301	-	$1 \leqslant F \leqslant 8$ FOR THE MOST PART THESE ARE SUPERVISED.
INCIPIENT FIRE DETECTION (IFD)	-	$1 \leqslant F \leqslant 2$ SAME AS ABOVE.
ZIU/FIU	99%	$1 \leqslant F$ SUPERVISED BY FIRE DEPARTMENT.
SPRINKLER(S) WET-PIPE (WITHOUT HEADS)	99.1%	$1 \leqslant F$ SUPERVISED BY IN-LINE PRESSURE SWITCHES.

TABLE 3 QUANTITATIVE RESULTS

THE PROBABILITY OF FAILURE (TO ACTIVATE AS REQUIRED) WAS CALCULATED ON A PER DEMAND BASIS OVER A FIFTEEN YEAR PERIOD. THE PROBABILITY OF INADVERTENT RELEASE WAS ESTIMATED ON A PER YEAR BASIS. THE RESULTS OF THE TWO ANALYSIS INDICATED THE FOLLOWING PROBABILITIES FOR THE 2XIIB DRY PIPE/PREACTION SYSTEM AND SHIVA'S WET PIPE SYSTEM.

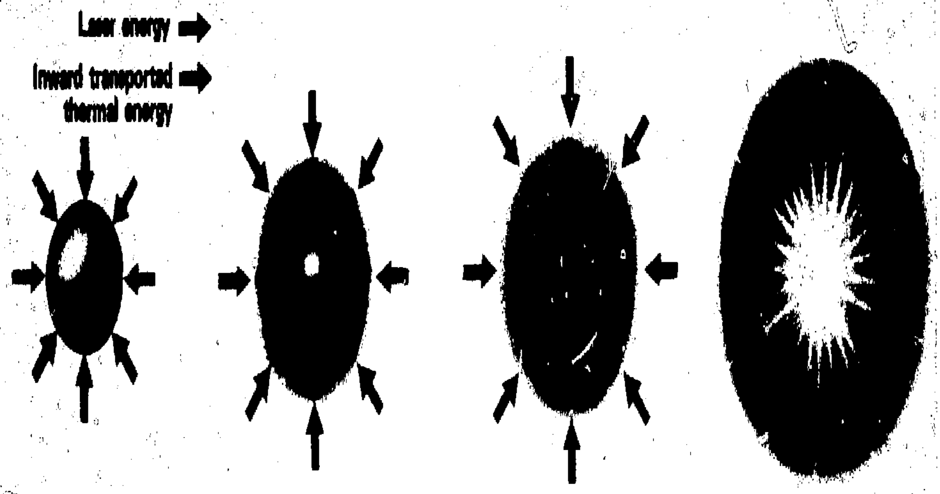
SYSTEM TYPE	PROBABILITY ESTIMATES	
	INABILITY TO OPERATE WHEN REQUIRED	INADVERTENT RELEASE
WET PIPE SPRINKLER SYSTEM (SHIVA)	02%	1.6×10^{-6}*
DRY PIPE/PREACTION SYSTEM (2XIIB)	18%	(LESS) THAN 10^{-6}

* "1967-1976 SPRINKLER LEAKAGE LOSSES (HEADS OPENED)". FACTORY MUTUAL RESEARCH 25 OCT. 1977. PREMATURE OPERATION DUE TO ALL CAUSES (OVER-HEATING, FREEZING, MECHANICAL INJURY, CORROSION, EXCESS PRESSURE, ETC.)

TABLE 4 SPRINKLER SYSTEM RELIABILITY COMPARISON WITH NFPA AND FACTORY MUTUAL STATISTICS

DATA SOURCE	PERIOD	NO. OF FIRES	% SATISFACTORY PERFORMANCE	FTA
NFPA	1924-1969	81,245	96.2	
AUSTRALIAN DATA	-	-	99.8	
UNITED KINGDOM	-	-	91.4	98%
FACTORY MUTUAL				
o WET-PIPE	1970-1977	2,442	91.5	
o DRY-PIPE		757	86.0	82%
o PRE-ACTION		7	85.7	

INERTIAL CONFINEMENT FUSION CONCEPT



Atmosphere Formation
Laser or particle beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

Compression
Fuel is compressed by rocket-like blowoff of the surface material.

Ignition
With the final driver pulse, the full core reaches 1000 – 10,000 times liquid density and ignites at 100,000,000°C.

Burn
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the driver input energy.

Figure 1.

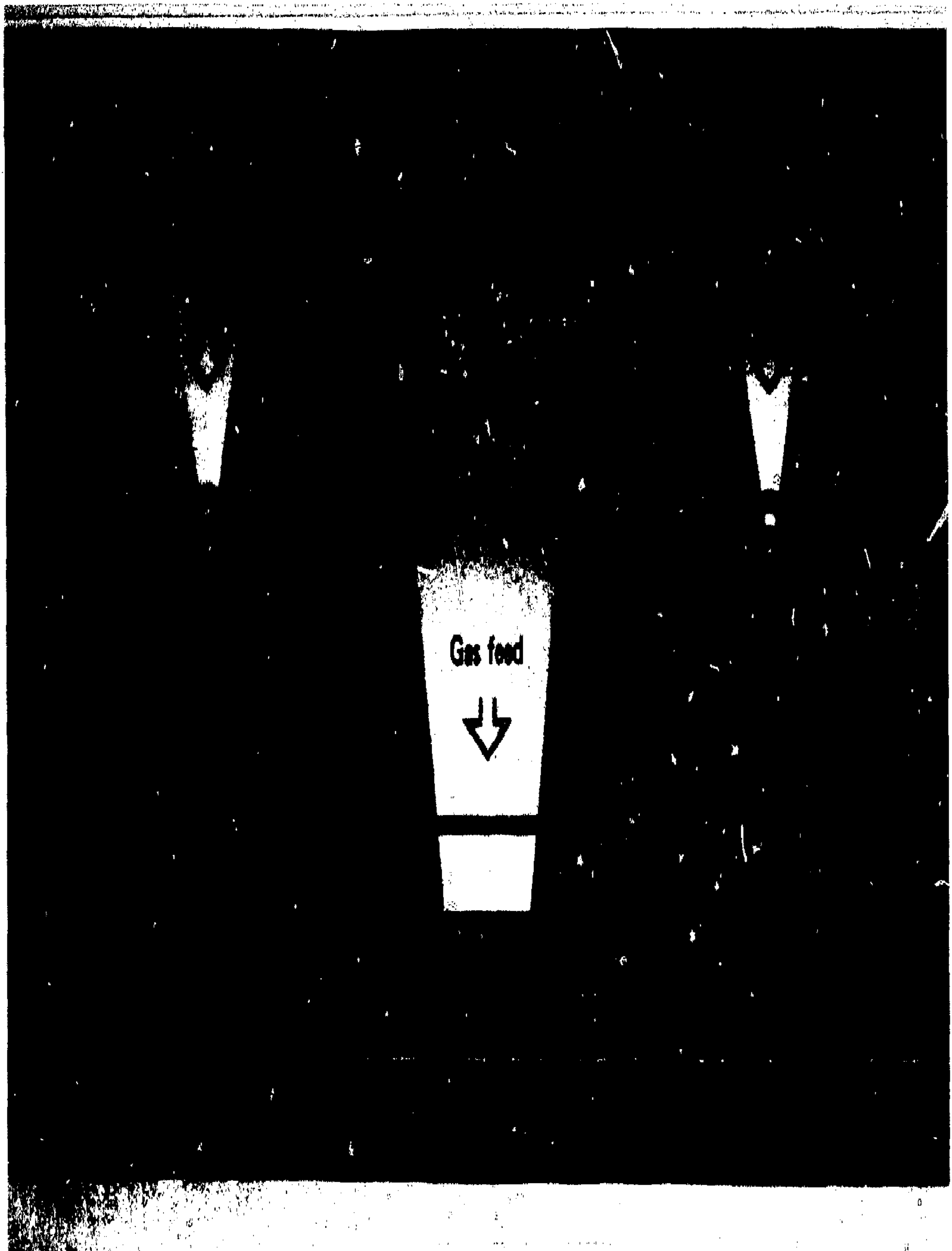


Figure 2.

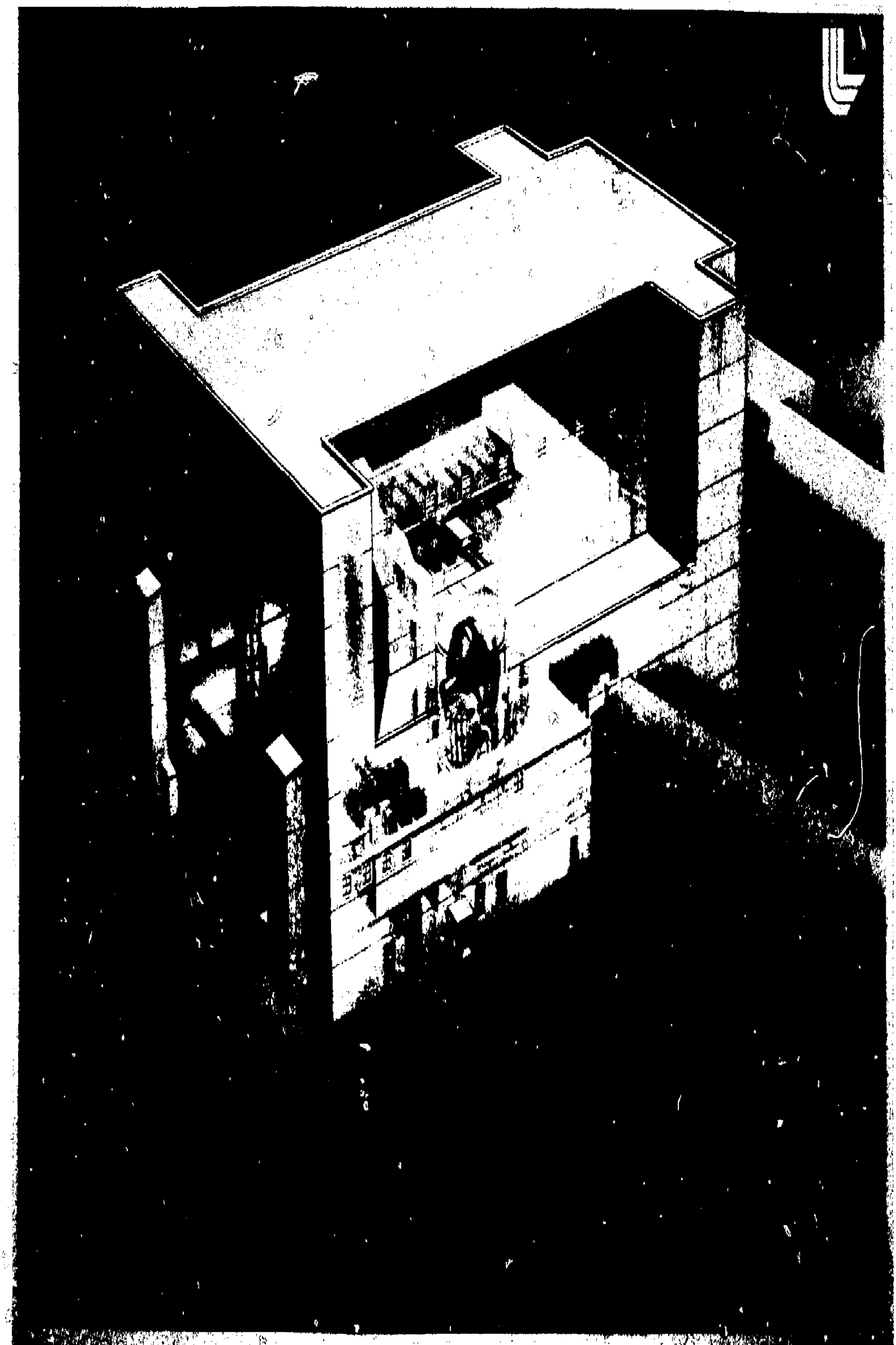


Figure 3.

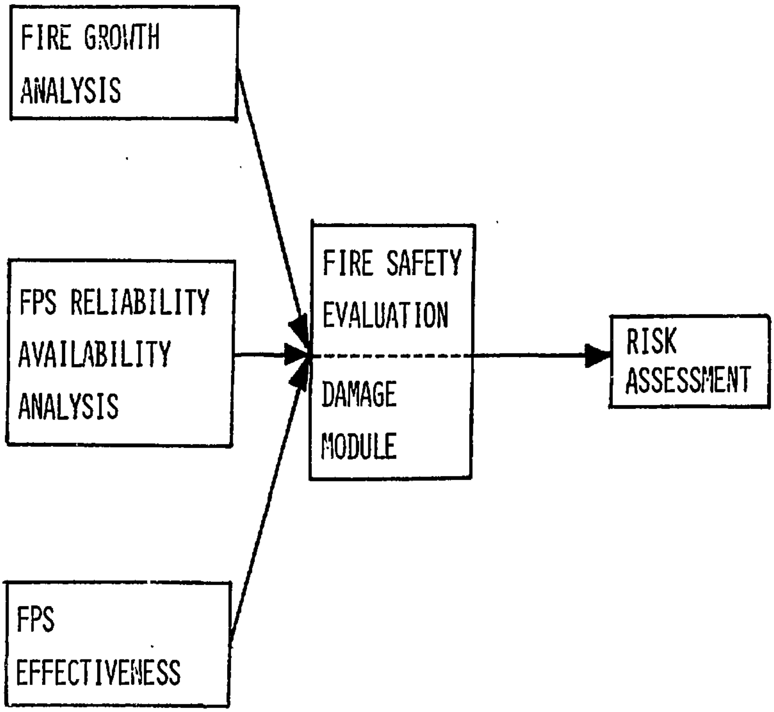

FIRE GROWTH ANALYSIS
FPS RELIABILITY AVAILABILITY ANALYSIS
FPS EFFECTIVENESS
FIRE SAFETY EVALUATION
DAMAGE MODULE
RISK ASSESSMENT

Figure 4

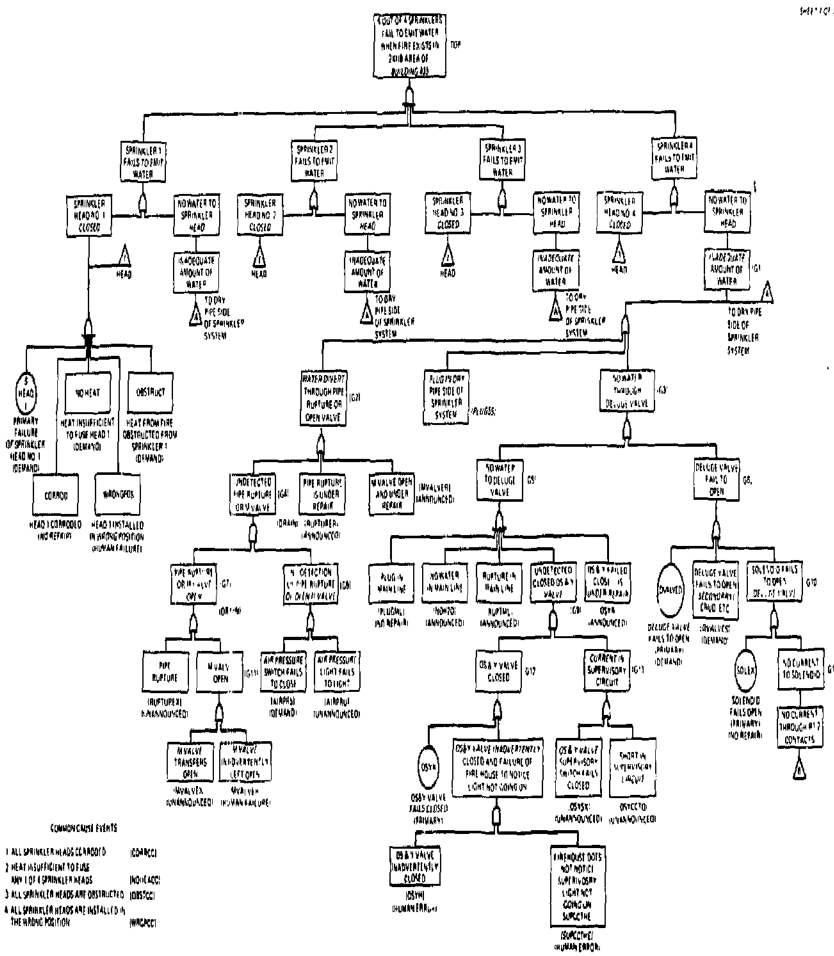
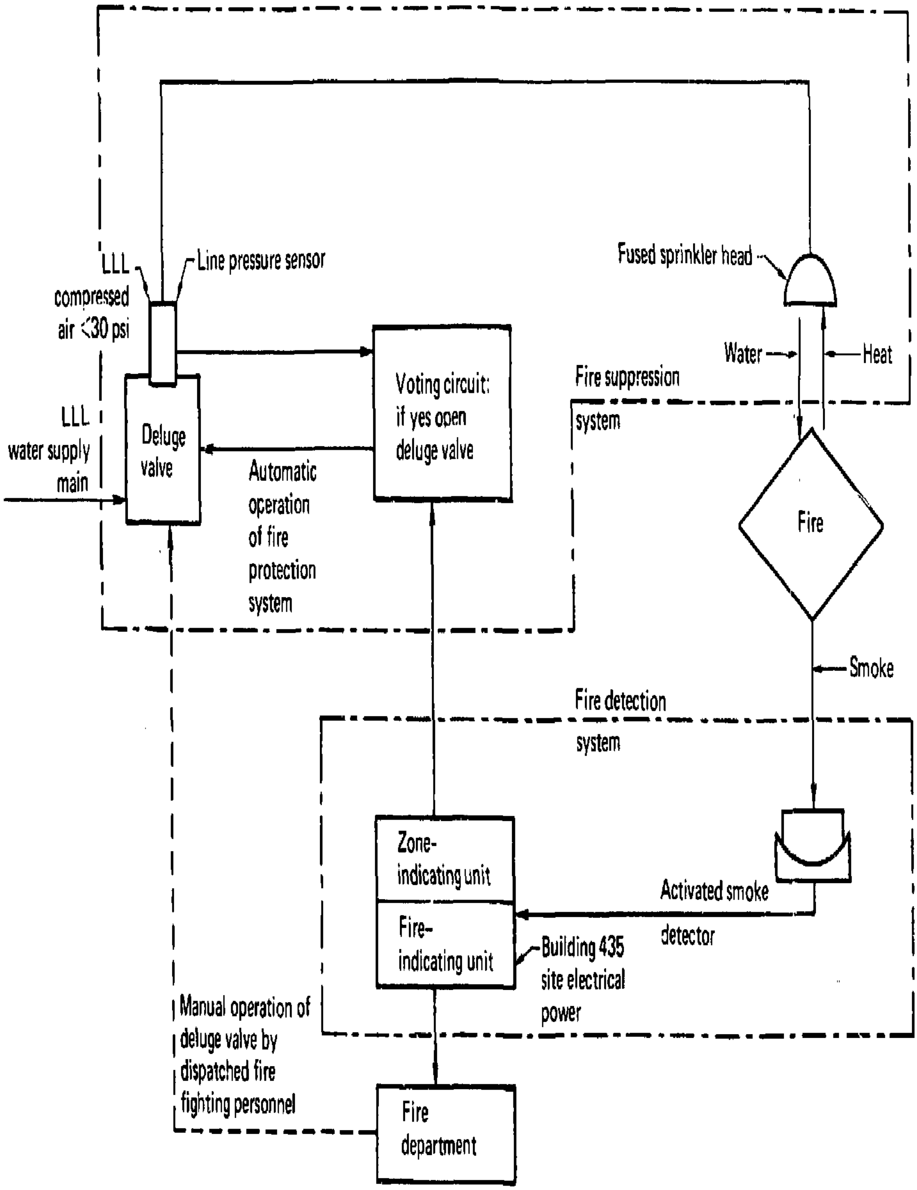
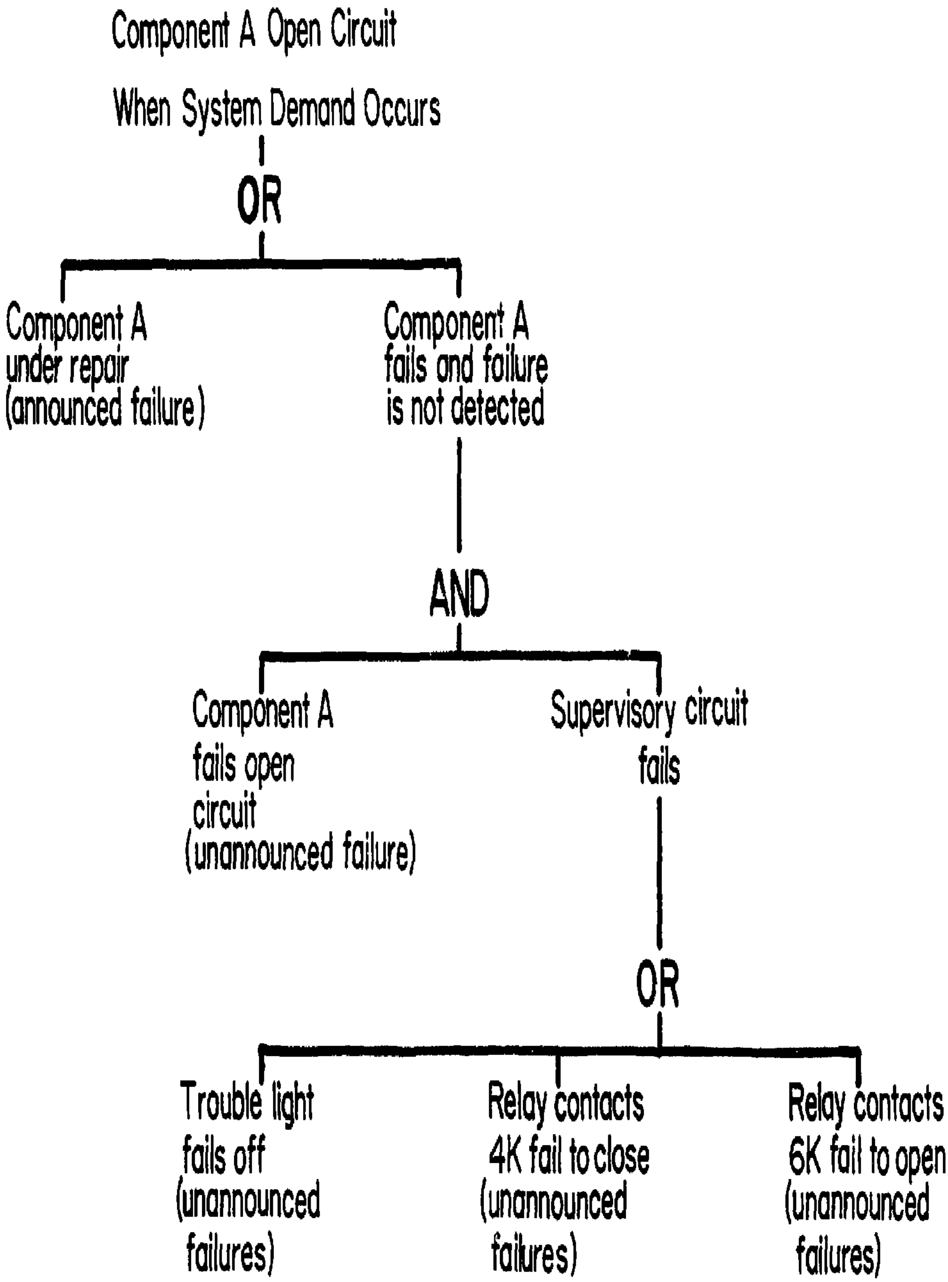


Figure 5



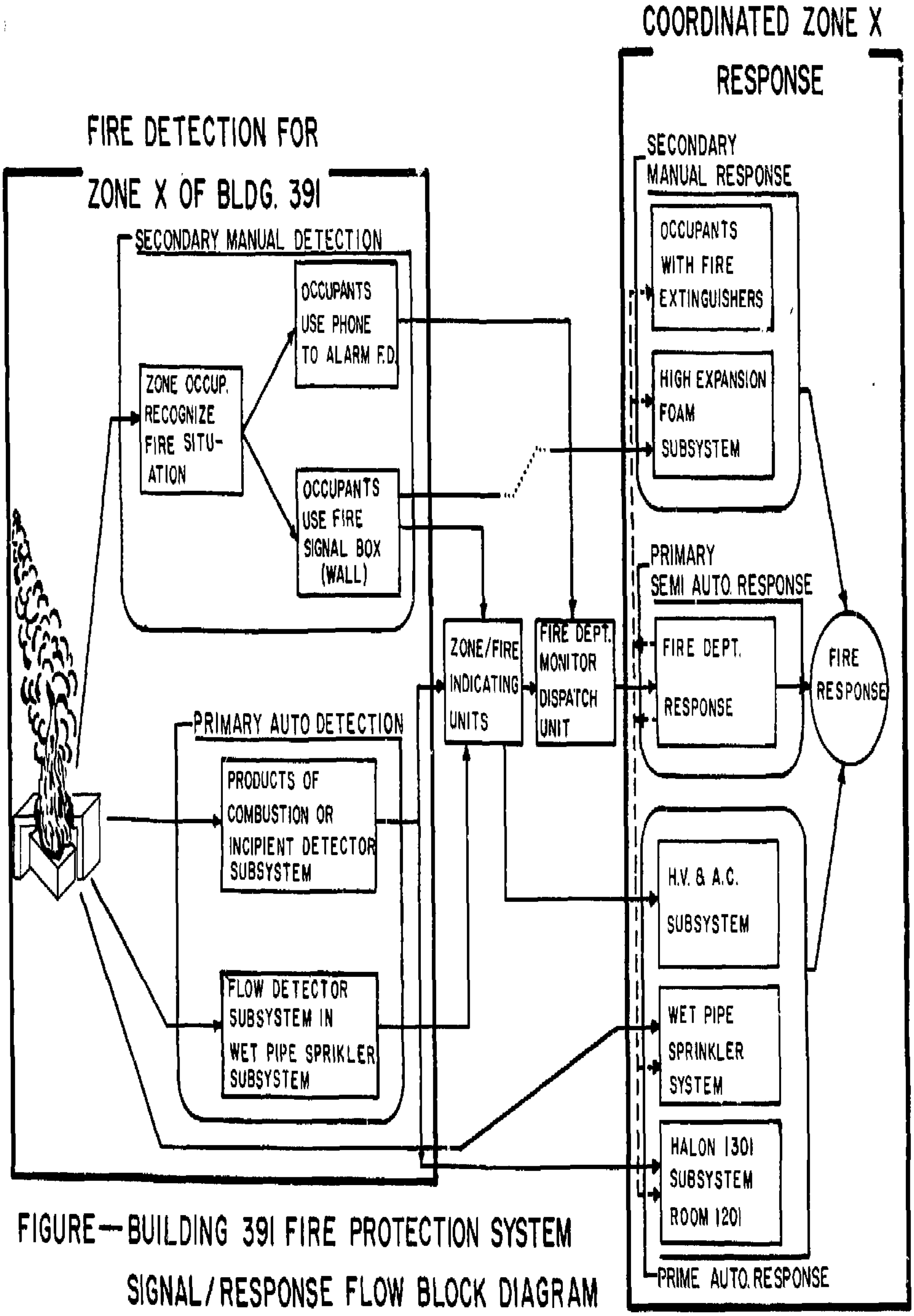
Schematic of 2XIIB Fire
Protection System

Figure 6



Generic Fault Tree

Figure 7



FIGURE—BUILDING 391 FIRE PROTECTION SYSTEM SIGNAL/RESPONSE FLOW BLOCK DIAGRAM

Figure 8

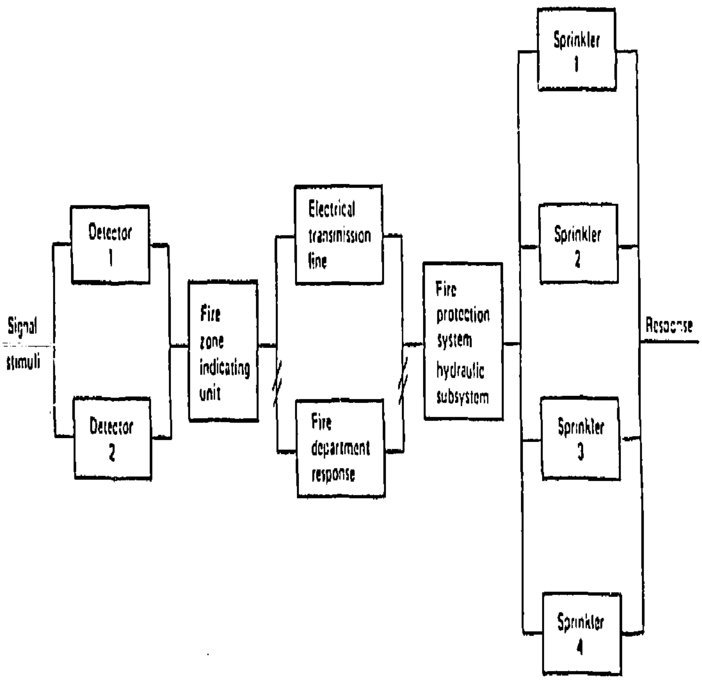


Figure 1 BLOCK DIAGRAM OF 2X2B's
DRY PIPE-PREACTION SPRINKLER SYSTEM

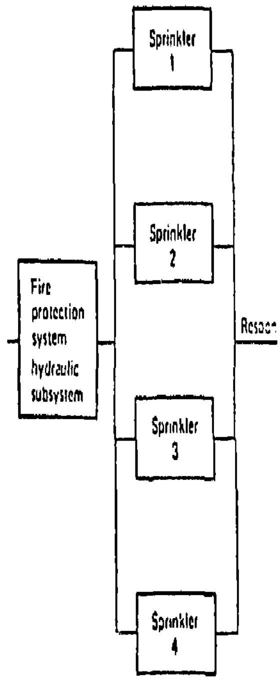


Figure 2 BLOCK DIAGRAM OF SHI
WET PIPE SPRINKLER SYSTEM

Figure 9

- EXISTING ENCLOSURE
- EXISTING FPS
- LITTLE PASSIVE FIRE PROTECTION (FIRE RATED BARRIERS, SEPARATION, STOPS, CABLETRAYS).
- DEPENDENCE OF AUTOMATIC SUPPRESSION SYSTEM.

- ENCLOSURE DESIGNED FOR EXPERIMENT.
- CONTEMPORARY FPS INCLUDED IN DESIGN PACKAGE.
- FIRE RATED BARRIERS AND OTHER PASSIVE PROTECTION.
- MULTI-FACET FPS STRATEGY, INDEPENDENT SYSTEM.

Figure 10

PROGRAM OBJECTIVES

A. MAJOR GOAL: PARALLEL DEVELOPMENT OF FIRE SAFETY WITH FUSION ENERGY TECHNOLOGY.

FAULT TREE ANALYSIS

B. DEFINE THE ENGINEERING PERFORMANCE OF STATE OF THE ART OF FIRE PROTECTION AS APPLIED TO FUSION ENERGY EXPERIMENTS.

C. DEVELOP RATIONAL METHODS OF ASSESSING FAULT MODES IN FIRE PROTECTION SYSTEMS.

FIRE GROWTH ANALYSIS

D. DEVELOP TECHNIQUES FOR DEFINING FIRE HAZARDS OF FEE.

E. COUPLE HAZARDS ANALYSIS WITH FIRE PROTECTION SYSTEMS ANALYSIS FOR LLNL FACILITIES.

FIRE SAFETY EVALUATION

F. DEVELOP SURVEY PROTOCOL FOR FEE'S AT NON-LLNL FACILITIES AND VALIDATE.

G. ANALYZE SURVEY RESULTS AND EVALUATE FIRE SAFETY OF EACH INSTALLATION.

H. CONDUCT RESEARCH TO SOLVE IDENTIFIED PROBLEMS.

Figure 11

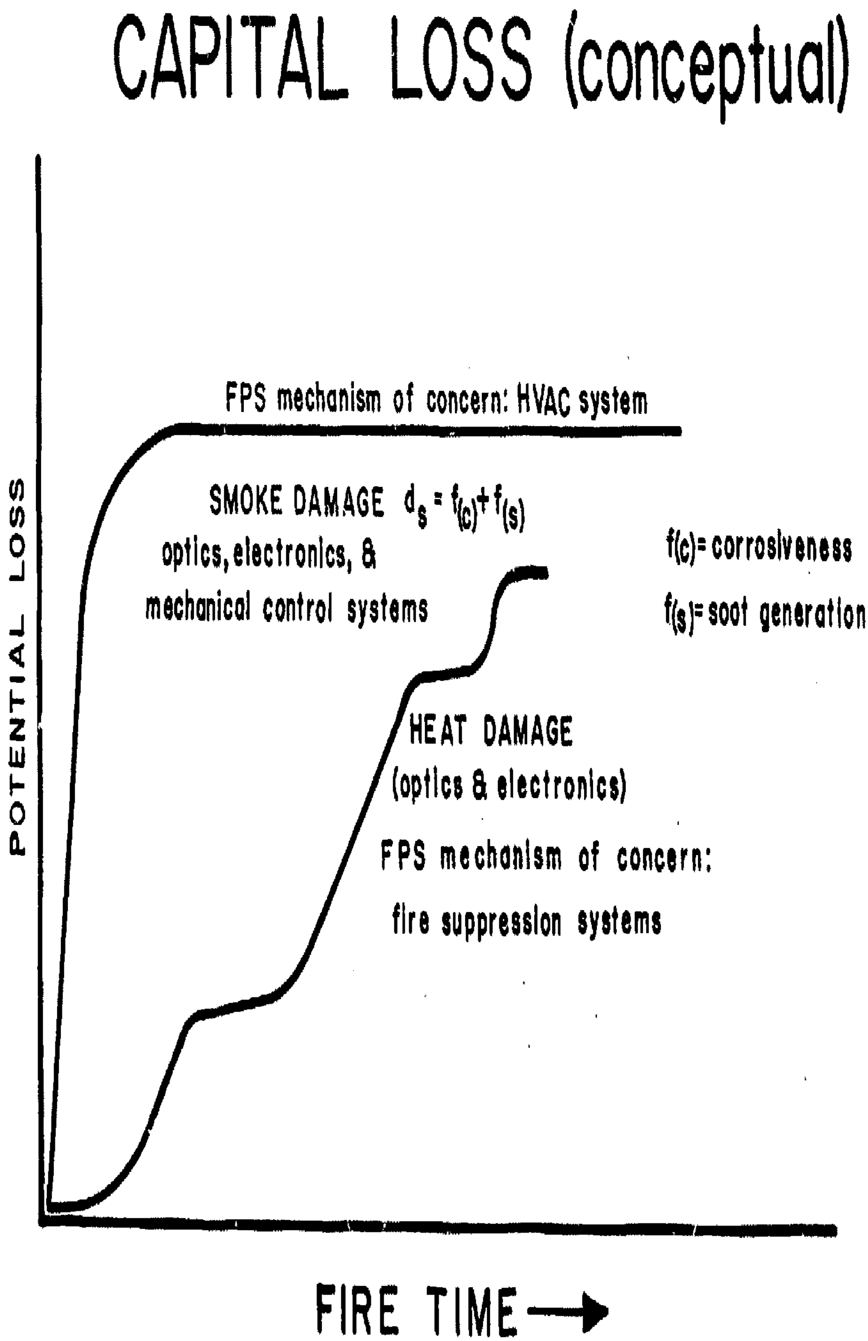

CAPITAL LOSS (conceptual)
FPS mechanism of concern: HVAC system
SMOKE DAMAGE $d_s = f_{(c)} + f_{(s)}$
optics, electronics, &
mechanical control systems
$f_{(c)}$= corrosiveness
$f_{(s)}$= soot generation
HEAT DAMAGE
(optics & electronics)
FPS mechanism of concern:
fire suppression systems
POTENTIAL LOSS
FIRE TIME →

Figure 12